Pacific Science (1974), Vol. 28, No. 3, p. 211–223
Printed in Great Britain

The Flood-Tide Jet in Fanning Island Lagoon[1]

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ABSTRACT: The flood-tide jet entering Fanning Island Lagoon is described and is shown to be effective in promoting exchange between lagoon and ocean water. The residence time of lagoon water must thus be substantially less than the maximum of 11 months suggested by earlier studies. The bathymetry of the lagoon area subject to the jet is described.

STUDIES of circulation and flushing of most atoll lagoons face severe problems: the boundary topography of reefs and deep passes is often complex; the details of the flow are complicated and rapidly varying; the area to be covered is so large that observation patterns require times long compared with the variations in flow; and there are only small differences between the characteristics of lagoon and ocean waters. Probably the most detailed lagoon circulation study has been that of Bikini (von Arx 1948); the results showed that exchange between ocean and lagoon was normally driven primarily by a combination of tidal flow through the passes and by wave-driven flow over the encircling reefs. For any specific atoll, the proportion of open interislet reefs to deep passes determines the relative importance of each of these exchange mechanisms. Von Arx showed that at Rongelap, where the passes are more important than those at Bikini, the flood tide generated a jetlike inflow that penetrated some 10 km into the lagoon.

Fanning Island (Fig. 1), located near 4° N, 159° W, is an abnormal atoll: continuous islets occupy nearly all of the encircling reefs, leaving only two shallow passes and one deep channel; also, there is a striking difference in turbidity between lagoon and ocean waters. These features make lagoon-ocean exchange much easier to study. Initial investigations were carried out during a cooperative University of Hawaii expedition to Fanning Island during 1970 (see *Pacific Science*, vol. 25, no. 2, 1971).

These studies showed that significant ocean-lagoon exchange occurs only through the deep pass at English Harbor (Gallagher et al. 1971). The primary question raised by this initial work involved the degree of mixing between lagoon water and ocean water that enters during each flood tide. This question of mixing arose in two different (but related) problems, both involved with attempts to determine overall lagoon calcification rates.

The first problem concerned the mean residence time of water in the lagoon. Gallagher et al. (1971) showed that if there were *no* mixing at English Harbor, so that flushing would be caused entirely by weak inflow through the two shallow passes, the residence time would be 11 months. Since some mixing actually must occur, the true residence time must be less than this maximum. (This point was insufficiently emphasized by Gallagher et al., and the 11-month figure has to some extent been misunderstood.)

The second problem involving mixing between lagoon and ocean water concerned the surprising indication that there was a net *influx* of suspended particulate calcium carbonate to the lagoon during the tidal cycle, even though visual observations suggested that water leaving English Harbor Pass on the ebb was much more turbid than that entering on the flood (Smith et al. 1971).

In response to these problems involving tidal mixing, an effort was made during a second (1972) University of Hawaii expedition to Fanning Island to develop a description of the jet of clear ocean water entering through

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[1] Hawaii Institute of Geophysics contribution no. 602. This study was supported by National Science Foundation grant no. GA-313111. Manuscript received 1 September 1973.
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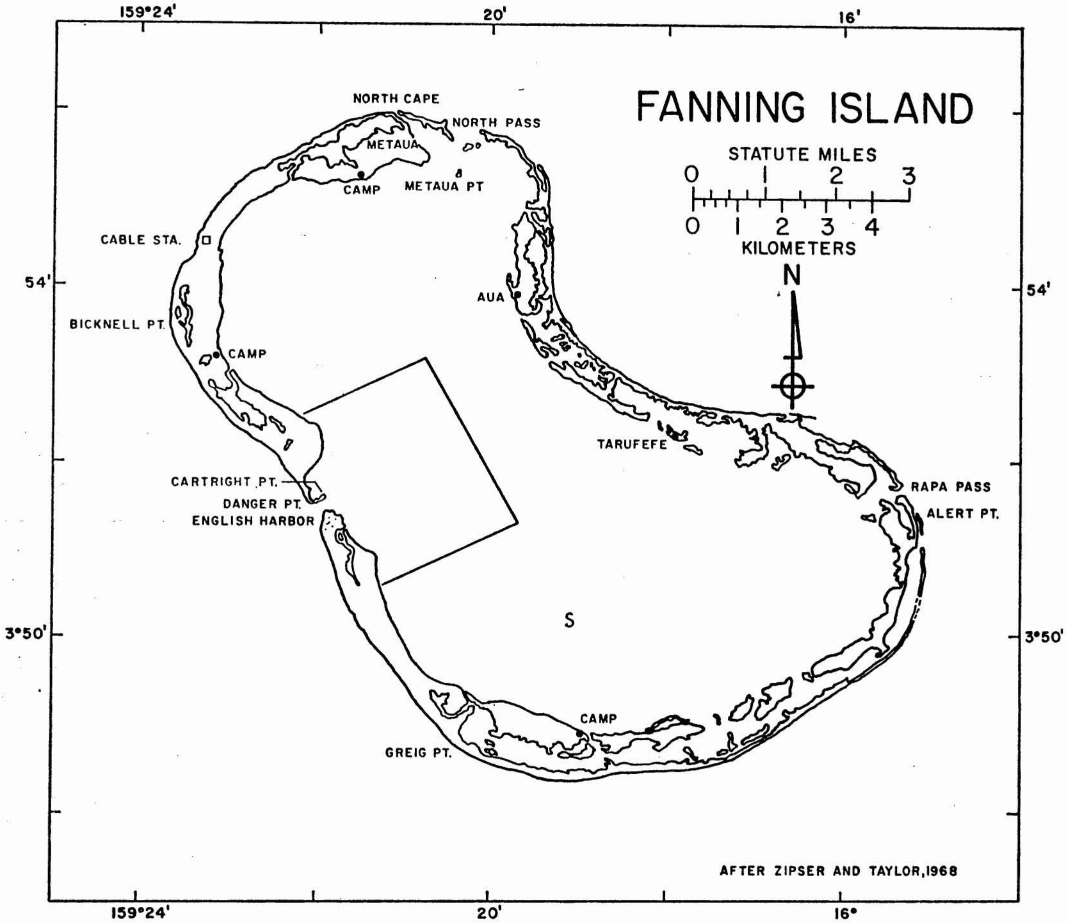

FIG. 1. Fanning Island. Heavy line approximately indicates the lagoon area near English Harbor covered by Figures 2, 4, and 8–11. The general area of sounding lines in the large south pond, discussed in the text, is shown by the letter "S."

English Harbor Pass on the flood, and to observe what happens to this water during the following ebb. The pattern of the jet was traced with an *in-situ* transmissometer (since the most striking difference between ocean and lagoon water is in the degree of turbidity) and by following drogues launched in and near the pass. Because bathymetric charts were inadequate, it was necessary to make a preliminary bathymetric survey of the area influenced by the jet.

BATHYMETRY

An array of day-beacons (locations shown in Fig. 2) was erected to allow position-fixing within the lagoon. Approximately 32 km of sounding lines were run with a Raytheon model DE-719 portable depth recorder from a small boat in the central lagoon area; the records were calibrated by direct measurements to a reflecting bar suspended at known depths. A complete bathymetric description of a complex coral-reef area such as this would have required far more time than was available. Our results, presented in Fig. 2, should be considered in the nature of a reasonably accurate sketch. Prominent points along the shallow reef edges were fixed during the survey, with oblique aerial photographs used to help draw in the shapes of the reefs between these points. Note that, because of the fundamental inadequacies of the survey, no correction to observed depths

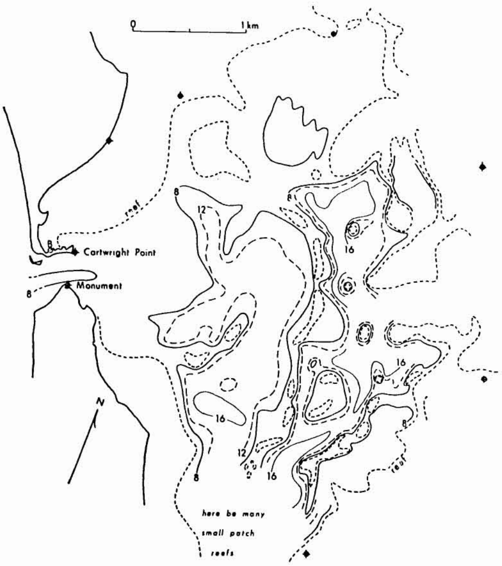

FIG. 2. English Harbor and vicinity. Short-dashed line represents approximate edge of shallow reef areas, drawn from aerial photographs and surveyed points. 8-, 12-, and 16-m contours shown; 4-m contour generally coincides closely with reef edge. Circled crosses represent navigational reference beacons; baseline for survey extends along Cartwright Point from point B to the tip.

was made for the small range of lagoon tide (mean range 34 cm; see Fig. 5).

RESULTS

English Harbor Pass

This narrow channel is deepest toward its southern side. Fig. 3 shows a section across the inner mouth, from Cartwright Point to the monument; the greatest depth is 10 m. The bottom is hard, with both dead and living coral; the very strong tidal currents permit little sediment accumulation. Movement of loose material can be heard underwater in the channel during the strong flow.

Sediment Fan

Inward from the pass the living coral gradually thins out and disappears, with sediment cover increasing. The sediment is coarse initially, becoming finer with distance from the high-velocity region close to the pass. A broad, nearly level fan of sediment extends into the lagoon, ending abruptly about 0.7 mile (1.1 km)

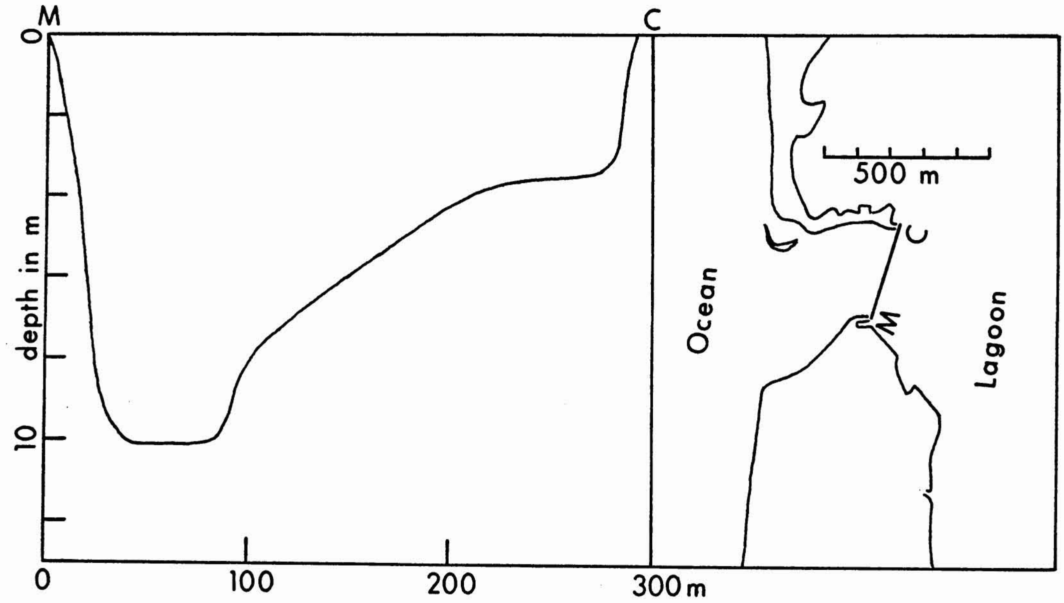

FIG. 3. Left: smoothed section across inner mouth of English Harbor Pass. Right: location of section. C, Cartwright Point; M, monument at tip of southern point.

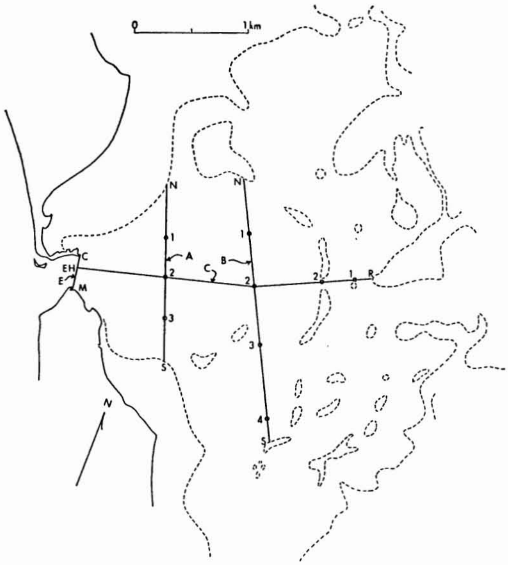

FIG. 4. Location of transmissivity lines, English Harbor area. Location references correspond to those in Figs. 6–7.

from the inner mouth of the pass. Depths over the sediment fan are 4–6 m.

English Harbor Main Basin

The main basin, inside of the sediment fan, is essentially free of obstructions over an area approximately 1.6 miles (2.6 km) north–south by 0.6 mile (1.0 km) east–west. The echo-sounder records indicate a generally smooth bottom with little development of living coral. Depths in the central part of the basin are about 12–16 m.

Inner Reef Line

The inner border of the main basin is marked by a nearly continuous curved line of shallow patch reefs, connected by slightly deeper saddles. Except for the wide, sandy flat on the large patch reef at the northern end of the line, these reefs support dense communities of living corals. A maze of small patch reefs extends between the southern end of the inner reef line and the fringing reef along the lagoon shore; no attempt was made to survey this complicated area.

Inner Deeps

Between the inner reef line and the elaborate complex of reefs and ponds that fill the remainder of Fanning Lagoon is an irregular series of small basins that contains the greatest depths recorded in the lagoon. The greatest individual recorded depth, located in the northern end of the line of inner deeps, was 19 m. The echo-sounding records suggest that the bottom in these basins consists largely of living coral, with a relief of 1–2 m.

The relatively great depths in these basins may result from the fact that, because of their proximity to English Harbor, they enjoy water with considerably lower average suspended sediment load than do the basins farther away from the pass, while at the same time they are protected by the inner reef line from the direct transport of coarser sediments.

Large South Pond

Several sounding lines were run in the large pond, which extends across most of the width of the lagoon, about halfway between English Harbor and Rapa Pass at the southeastern end of the atoll (Fig. 1). Only subsequently, when, using shoreline features, we attempted to extend our triangulation net to this area, did we discover that we were accumulating significant errors. Therefore, we are not presenting a chart of this area. Observed depths in the pond were mostly near 8 m, with fluctuations between 4 m and 12 m. The bottom was characterized by great small-scale irregularity, which indicates a substantial cover of live coral, with a relief of 2–3 m.

TRANSMISSIVITY OBSERVATIONS

Methods

The development and mixing of the incoming, clear-water tidal "jet" were observed with a portable transmissometer (Hydro Products model 612, 1-m path-length). Measured transmissivities ranged from about 12 percent in Suez Pond (near the middle of the northern part of the lagoon) to almost 65 percent in the incoming ocean water.

A pattern of lines (Fig. 4) was set up along and across the path of the incoming jet. These

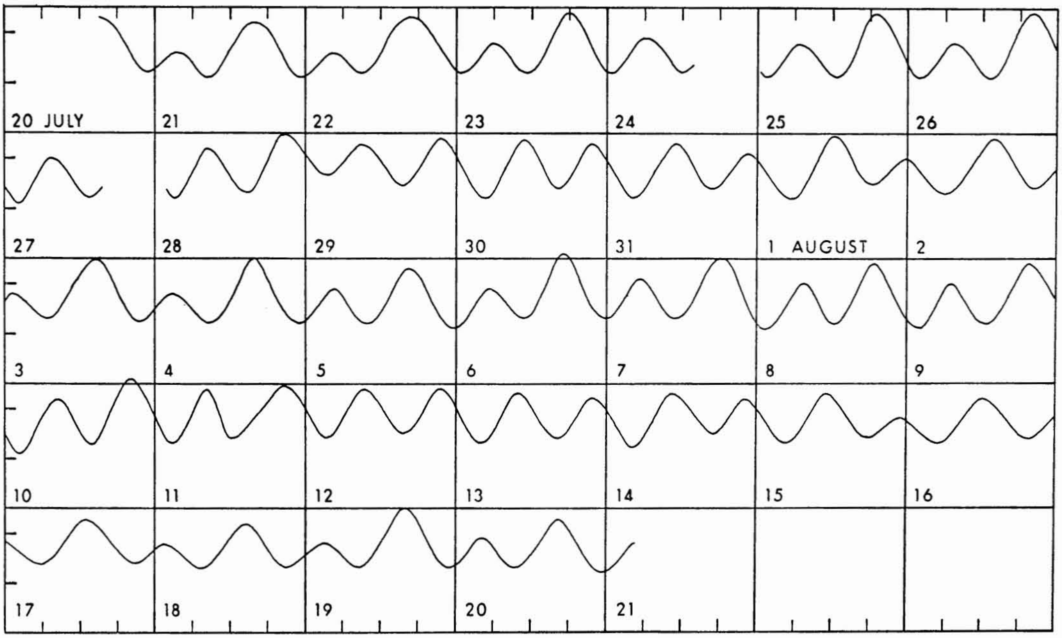

FIG. 5. Smoothed record of Fanning Island lagoon tide recorded at the cable station (Fig. 1). Ticks represent 1 foot on arbitrary vertical scale.

lines were marked by a series of anchored buoys and natural features. (Note that the later drogue studies confirmed our choice of our longitudinal track, line C.) The lines were run at constant speed, with readings from the towed transmissometer taken at fixed time-intervals. The time at which the boat passed the buoys or other marks was also recorded, so that the positions of the instrument readings could be interpolated along the lines. All readings were made with the instrument towed at a depth of 1–2 m, since the initial trials had shown little variation of transmissivity with depth in the areas studied.

Readings were taken at 30-sec intervals (approximately 75 m) along lines A, B, and C. Along line E, across the inner mouth of English Harbor Pass, the readings were taken at 15-sec intervals (approximately 40 m), and the position of the boat along the line was monitored by radio signals from a sighting station on shore.

Lines E and A were run at approximately 2-hour intervals during a complete flood-ebb cycle, extending from dawn to dusk on 17 August. Additional buoys were positioned and fixed on 18 August, and lines A, B, and C were run three times during flood tide on 19 August. (Fig. 5 gives the lagoon tide for these dates.)

Transmissivity was also determined during drogue studies which followed the tidal-jet observations; these data will be discussed in conjunction with the drogue results.

A recording tide station was maintained at the cable station (Fig. 1) lagoon pier from 20 July until 21 August. The smoothed record is presented in Fig. 5. The mean range was 34 cm, the maximum range over a single tide was 40 cm, and the minimum was 12 cm. Gallagher et al. (1971) showed that the lagoon tide range is about half that of the ocean outside, with a variable lag of up to approximately 3 h. Tide records were made at the north side of Cartwright Point (Fig. 1) from 24 July until 9 August. No significant differences were observed between these locations, so that the cable station records can be taken as representative of the lagoon as a whole.

Results

The data from the individual transmissivity runs are presented in Figs. 6 and 7. These

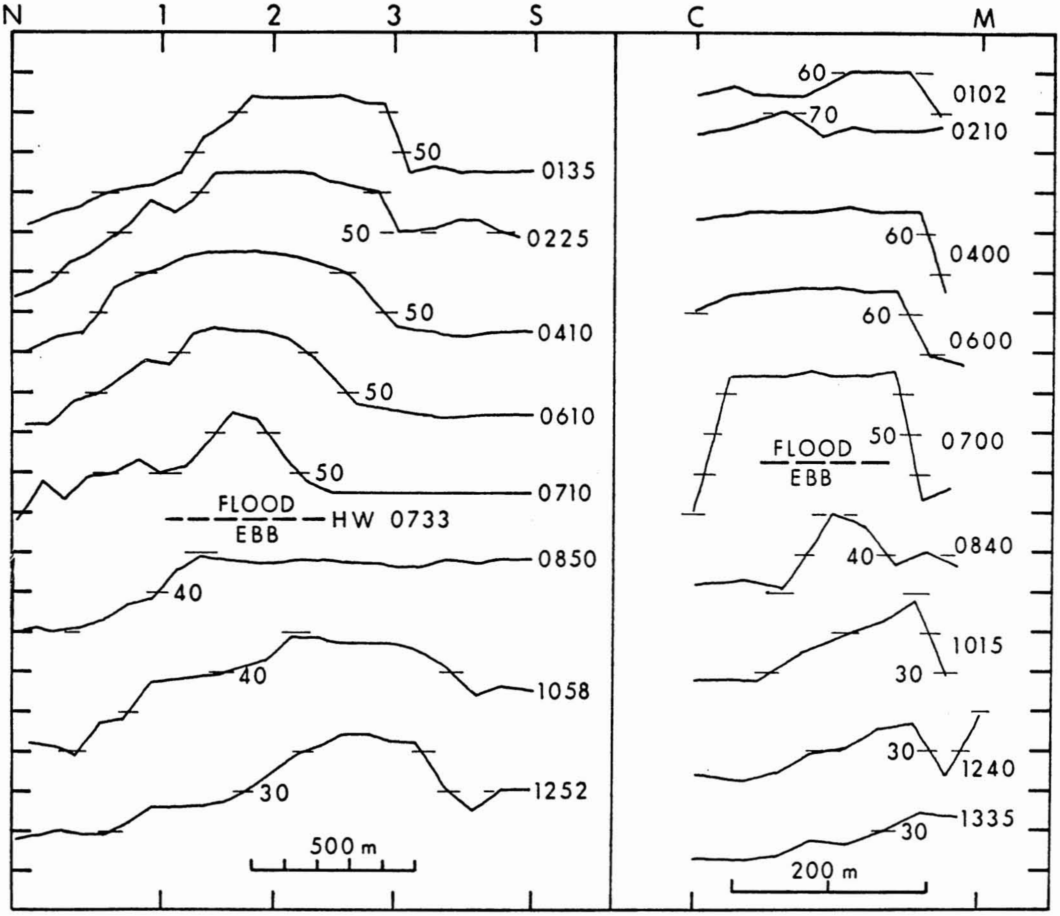

FIG. 6. Transmissivity data, 17 August 1972. Location references correspond to map in Fig. 4. Each run identified at its right end by hours and minutes since low water (0600 local time). Transmissivity given by ticks separated by 10 percent; reference value given alongside each line. Left: line A. Right: line E. Note difference in horizontal scale.

distributions were used to develop the overall patterns of transmissivity described below, and the individual lines are discussed in conjunction with these patterns.

In developing the overall patterns, adjustments had to be made to correct for the time interval between lines. All available subsidiary information was used in making these adjustments, but, because of the large and rapid changes which occur at the turn of the tide and because of the natural variability of this turbulent regime, subjective judgment played a significant role. The patterns should be regarded as interpretive summaries of the observations.

LOW WATER: Figure 8 is based primarily on data from lines A and B, 19 August, run 0.5 and 0.8 h, respectively, after low-water slack, plus data from an initial random observation pattern.

Turbid water is found extending along the lagoon shores and into the English Harbor Pass (see the last few transects on line E, Fig. 6). A pool of relatively clear water remains back in the main basin, with variable transmissivity being generally in the range 40–50 percent. This water is seen toward the right (inner) end of line C, first transect on 19 August. (Note that this transect was not otherwise used in drawing Fig. 8, since the flood had already started; ocean water is evident in the high

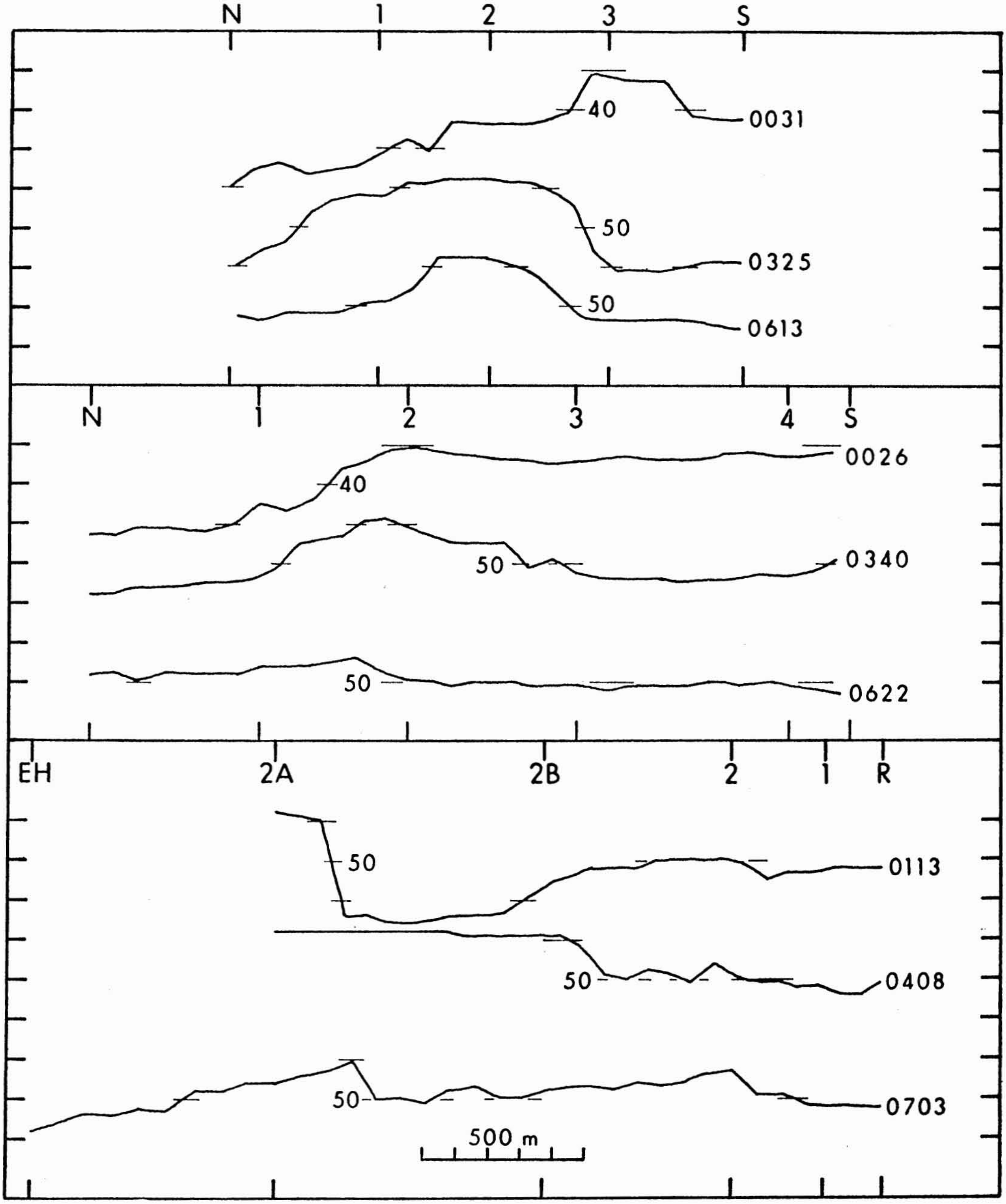

FIG. 7. Transmissivity data, 19 August 1972. Low water was 0840 local time. Top: line A. Middle: line B. Bottom: line C.

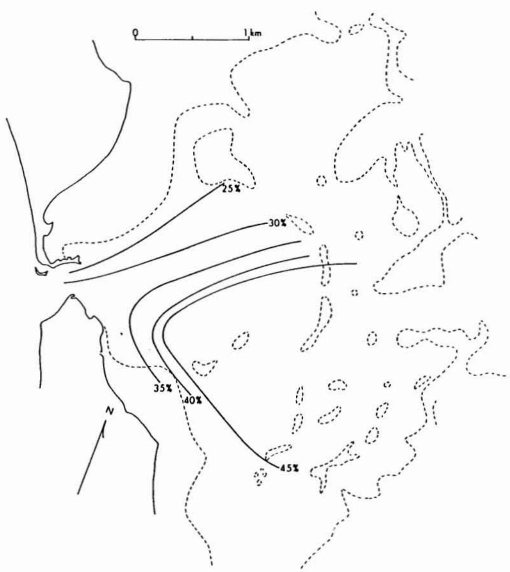

FIG. 8. Smoothed low water transmissivity pattern, English Harbor area.

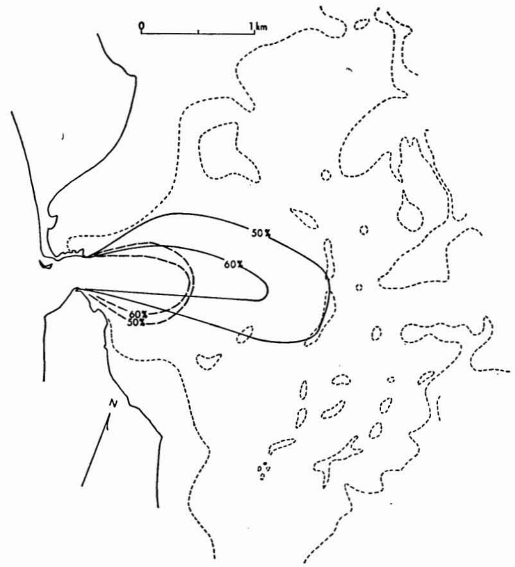

FIG. 9. Smoothed flood tide transmissivity patterns, English Harbor area. Dashed lines, approximately 1 h after low water; solid lines, approximately 3.5 h after low water.

transmissivities at the left [oceanward] end of the line.)

FLOOD TIDE: The penetration of ocean water into the lagoon is shown in Fig. 9 for approximately 1.5 h and 3.5 h after low-water slack. The distribution at 1.5 h is based on line C, 19 August, 1.2 h after slack; and line A, 17 August, 1.6 h after slack. The 3.5 h distribution is based on lines A, B, and C, 19 August, at 3.4, 3.7, and 4.1 h after slack, respectively. Both line E data and visual observations were used to extend the distributions to the vicinity of English Harbor Pass.

The incoming flow develops rapidly and advances across the relatively shallow sediment fan at high speed. Sharp fronts can initially develop between the ocean water and the turbid water remaining near the pass from the previous ebb (see line C, first run, and the drogue results below). Such fronts were observed repeatedly near the inner edge of the sediment fan, where the sudden depth increase leads to a sharp drop in the velocity of the inflow.

As it leaves the pass, the inflow takes the form of a distinct jet of clear water, separated from the relatively still water on either side by violent, narrow, shear zones which broaden and become less energetic with distance inward. Turbid lagoon water is entrained in these turbulent shear zones on both sides of the neck of the jet, so that a compensating flow of this turbid water develops, moving relatively slowly along the lagoon shores toward the pass from the north and south.

As the flood continues, the incoming water extends across the fan and the main basin. The vigorous lateral turbulence at the sides of the jet continues to entrain turbid water and to mix it into the inflow. By the time the water has crossed the main basin, its transmissivity has been decreased to approximately 50 percent; see line C at 4.1 h. Unmixed ocean water (over 60-percent transmissivity) can be identified on this line to a position slightly beyond the crossing with line B, about 75 percent of the way from English Harbor Pass to the inner reef line.

The extent of the unmixed water represents a balance between the rate of inflow and the rate of mixing with lagoon water. During the latter part of the flood period the rate of inflow is decreasing, while the mixing is still vigorous; as shown by the distributions of transmissivity (Fig. 7 especially line A), the extent of unmixed

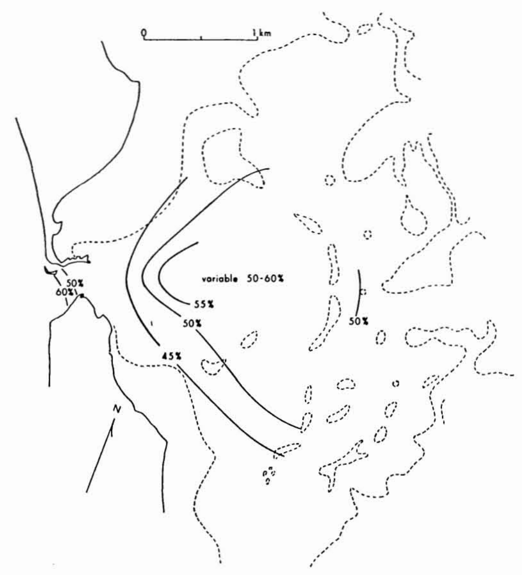

FIG. 10. Smoothed high water transmissivity pattern, English Harbor area. Contours within the pass estimated; conditions here change rapidly with the turn of tide.

water is decreasing during this period. It seems likely that the 3.5-h distribution shown in Fig. 9 represents close to an average maximum extent for the unmixed water, although some probably occasionally gets as far as the inner reef line.

Time did not permit studies of the inflow after it had passed beyond the main basin, but the few measurements available plus visual observations suggest that the lagoon line reefs act as very effective turbulence-inducing baffles, causing the water which accelerates as it crosses them to mix rapidly with the water in the pond on the far side. Visual observations of foam lines, indicating sharp convergences, lying along the inner edge of line reefs were made on several occasions during flood tide. The result of this mixing is a seeming tendency for transmissivity to change discontinuously from pond to pond (see discussion below of drogue run B). More observations are needed to confirm this feature.

HIGH WATER: Figure 10 is based primarily on data from lines A, B, and C, 19 August, run 6.2, 6.5, and 7.1 hours, respectively, after low-water slack. Ebb flow began in the middle of the run and was well developed by the completion of line C. The transmissivities of over 60 percent on line A were ignored, since the last of the flood was still flowing across this line at the time it was run.

The main basin is filled with ocean water which has been mixed with a relatively small component of lagoon water entrained in the jet; transmissivities in the basin are 50–60 percent. As described above, entrainment into the jet during flood tide has maintained high-turbidity water along the lagoon shore immediately to either side of the pass. At high-water slack, this turbid water mixes rapidly across the former path of the jet, sharply decreasing the transmissivity just within the lagoon from the pass, and separating the moderately clear water now filling the main basin from the ocean water outside.

EBB TIDE: The ebb period was followed only on lines E and A (Figs. 6 and 7). Within the pass (line E), as the ebb begins it immediately draws on the very turbid water to the north and south, along the lagoon shore, as well as on the less turbid mixed water directly inward from the pass. As the water approaches the pass, the lateral convergence and longitudinal acceleration greatly intensify the lateral turbidity gradients. The resultant distribution, with turbid water flowing out along either side of the pass and clearer water in the middle, is visually striking; this can also be seen in the line E curves at 8.7 and 10.8 h, although the actual gradients were sharper than indicated by these 15-sec observations. Later during the ebb the water approaching the pass is older, in terms of lagoon residence, and such sharp gradients in turbidity have been eliminated by mixing. The general level of turbidity also increases during the ebb, as water from farther within the lagoon reaches the pass.

Similar, but much broader, patterns can be seen along line A (Fig. 7), which lies across the ebb flow approaching the pass. Mixed water from the main basin (transmissivity 40–50 percent) can be seen near the center of the line; toward either end one sees turbid water approaching the pass from north and south. The turbidity increases during the ebb, as water from farther within the lagoon crosses line A.

DROGUE OBSERVATIONS

Methods

Drogues were used to follow the water entering the lagoon during flood tide. The drogues were in the form of crossed muslin panels, 6 feet square, extended top and bottom by crossed bamboo poles. The drogues were weighted at the bottom and buoyed at the top, with the combination adjusted to be slightly heavy in the water. The entire assembly was then suspended by a light 6-foot line from a single 1-gallon plastic "bleach bottle" at the surface. At this depth the drogues were roughly centered in the water column over the shallow part of the sediment fan.

Six drogue-runs were completed during the period 15 to 20 August. All drogues were launched in or near the English Harbor Pass, during flood tide. The drogue tracks are shown in Fig. 11. Fixes are identified by number along each track. Table 1 gives time of each fix, mean speed since the previous fix, transmissivity measured at each fix, and remarks on each drogue run.

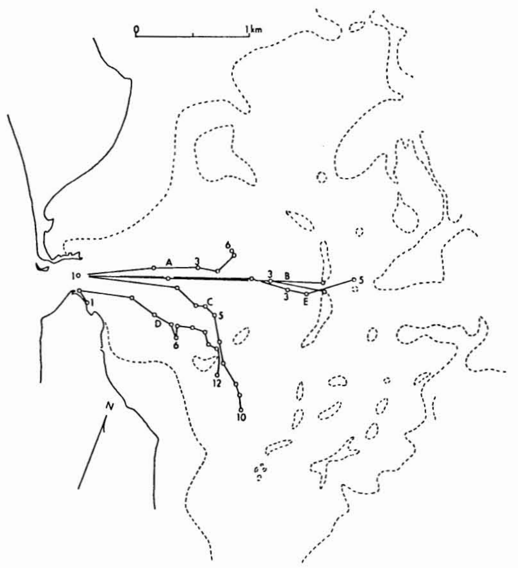

Fig. 11. Drogue tracks, flood tide, English Harbor area. Drogue runs indicated by letters; selected fixes identified by numbers along each track. Data on individual runs given in Table 1.

Results

All drogues launched in the pass moved rapidly inward with the flood. The launching was made in the center of the channel, as estimated by eye; it was impossible to anchor or to control position exactly in the very strong current.

Two of these releases (tracks B and E, Fig. 11; note that track B represents two drogues launched close together) produced tracks extending straight across the main basin. These drogues essentially followed the track that we had earlier established as transmissometer line C; drogue E actually passed through the gap in the inner reef line that we had used for line C.

One of the midpass releases (track A, Fig. 11) was late during the flood period; this drogue slowed rapidly and at high-water slack had only reached the edge of the main basin, where it turned northward.

The final midpass release (track C, Fig. 11) was made in conjunction with a release just outside the jet (see description of track D, following). Drogue C travelled slightly south of the direct inward line until it reached the main basin, where it slowed and turned sharply south, leaving the main jet.

Drogue D (Fig. 11) was launched in the turbid water just south of the pass. This drogue moved toward the pass and entered the violent shear zone at the edge of the jet only some 15 m from the end of the point off the English Harbor monument. The drogue was pulled under, surfacing about 1 minute later approximately 100 m downstream. (Drogue C was launched in midpass at approximately the time that D entered the edge of the jet.) Drogue D moved to the south, apparently at one point getting caught in an eddy for half an hour. D lagged and stayed to the right of the track of C. Both drogues passed between the two patch reefs south of the pass.

Note that a second drogue was launched in the turbid water south of the jet; this also moved to the jet and entered the shear zone, but it was pulled down, snagged on the bottom, and destroyed. No drogues were released in the turbid water north of the jet because of insufficient water depth.

TABLE 1

DROGUE-TRACK DATA

DROGUE AND DATE	FIX	TIME	SPEED (cm/sec)	TRANS-MISSIVITY (%)	REMARKS
Drogue A, 15 Aug. 1972	1	1045	—	64	launched midpass near end of flood
	2	1103	62	—	
	3	1118	42	—	
	4	1122	42	—	at visible front
	5	1208	10	—	ebb beginning (high water 1125)
	6	1229	neglig.	—	end
Drogue B,* 16 Aug. 1972	1	0845	—	64	launched midpass, approx. 3 h after low water
	2	0905	120	65	visible front observed at edge of main basin
	3	0951	32	64	at front with transmissivity dropping to 60 percent
	4	1040	16	60	end at sides of gap in inner reef line (high water 1220)
Drogue C, 20 Aug. 1972	1	1112	—	62	launched midpass, approx. 1 h after low water
	2	1128	91	63	
	3	1140	32	63	approaching front with transmissivity dropping to 44 percent
	4	1146	–	–	
	5	1210	8	53	still near front, turning to south
	6	1230	20	55	visible front dissipated
	7	1242	27	56	passed between
	8	1255	28	56	
	9	1305	16	48	
	10	1325	11	45	end (high water 1640)
Drogue D, 20 Aug. 1972	1	1055	–	43	launched in turbid water south of pass, approx. 1 h after low water
	2	1110	14	–	caught in turbulent shear zone at edge of jet, briefly submerged; drogue C launched
	3	1116	58	58	
	4	1125	45	60	
	5	1131	47	59	
	6	1152	10	50	
	7	1214	7	50	eddy?
	8	1225	20	51	
	9	1236	18	53	
	10	1247	17	55	
	11	1300	11	53	
	12	1332	13	53	end (high water 1640)
Drogue E, 20 Aug. 1972	1	1350	–	64	launched midpass, approx. 4 h after low water
	2	1426	71	62	
	3	1445	29	60	
	4	1512	11	59	approaching gap in inner reef line
	5	1555	17	57	end on far side of inner reef line (high water 1640)

NOTE: Time is local; speed is average since previous fix; transmissivity was measured at fix. See Fig. 11.
* Two adjacent drogues diverged only after fix 3.

Transmissivity along Drogue Tracks

All midpass drogue launches were in unmixed incoming ocean water, with transmissivity near 64 percent. Drogues A, B (a close pair), and C encountered visible fronts between ocean water and more turbid water; in each case these fronts were first observed near the point at which the drogue left the sediment fan and moved over the greater depth of the main basin. Transmissivity dropped from 5 to 20 percent across the fronts. The encounter with a front coincided with the sharp northward turn of drogue A and the similar southward turn of C. In the case of B, the front was observed to be moving away from the pass, ahead of the incoming water. Lateral mixing was increasing the turbidity of the moving water, however, so that when drogues B had crossed the main basin and reached the inner reef line most of the water in the basin behind them had transmissivity reduced to near 55 percent. (This was approaching the time of high-water slack.)

Drogue E, launched late during the flood period, did not encounter a visible front; transmissivity decreased gradually to 57 percent on the far side of the inner reef line, at a time within 1 hour of high-water slack. Note that during drogue run B, relatively earlier in the flood period, a visible turbidity change was observed across the inner reef line, with transmissivity dropping from 58 percent to 45–48 percent across the reefs. During run E, late in the flood, the transmissivities had increased and no sharp change was observed across the reef line.

The fronts are obviously transient, rapidly changing phenomena; no clear idea of their pattern can be gained from the limited viewpoint of a single boat. The tendency for the fronts to appear first at the edge of the main basin is probably associated with the sudden slowing of the inflow because of the sharp increase in depth, as mentioned earlier. The most intense front observed was that encountered by drogue C. Transmissivity decreased from 63 to 44 percent across this front, which was observed underwater; the ocean water was slightly underrunning the turbid water, with the frontal surface sloping steeply down (approximately 45°) toward the lagoon. The drogue crossed the surface line of the front and then remained near it; within an hour all evidence of the front had dissipated and the transmissivity near the drogue was 55 percent. Transmissivity near drogue C decreased rapidly after the drogue passed south between the patch reefs, reaching a value of 45 percent at the time the drogue was retrieved.

Drogue D was launched just south of the jet in water with transmissivity of 43 percent. Immediately after the drogue was caught in the shear zone, the transmissivity by it was 58 percent, indicative of the rapid mixing at the sides of the jet. Transmissivity remained 58–60 percent until the drogue paused (in an eddy?), where transmissivity dropped to 50 percent. Transmissivity remained in the range 50–55 percent as the drogue moved southward. No visible front was observed along this track.

SUMMARY

The Tidal Jet

Tidal flow through English Harbor Pass is effective in bringing about an exchange between ocean and lagoon. This exchange involves two processes.

One process is associated with vigorous lateral mixing generated along either side of the incoming jet. Even as the ebb begins, there is no unmixed ocean water from the preceding flood found within the lagoon.

The second process involves the patterns of flow water near the pass. During the flood, the inflowing narrow jet injects clear ocean water well back into the lagoon. At the same time, turbid lagoon water is drawn along the lagoon shore toward the pass, from both sides, by the entrainment occurring along the edges of the jet. During the ebb, the outflow draws water broadly from the area surrounding the inner mouth of the pass. The outflow thus comprises a sizeable component of turbid lagoon water, as well as some of the (already partially mixed) ocean water from the preceding flood. At the end of the ebb, some of the water from the preceding flood still remains in the main basin, directly inward from the pass. This water is pushed still farther into the lagoon by the following flood, with mixing enhanced by the complex, interconnected pattern of shallow line reefs.

Quantitative estimates of proportions of lagoon and ocean water passing out during the ebb (that is, of the rate of exchange associated with tidal flushing) await further attempts to quantify the values of transmissivity in terms of suspended particulate load. An attempt to do this during the second expedition proved to be inadequate. Subsequent data from Canton Island Lagoon (S. V. Smith, personal communication), which exhibits a turbidity contrast visually similar to that at Fanning Island, showed the following approximate relationships: 12-percent transmissivity (corresponding to interior lagoon water at Fanning Island), 2,000 μg $CaCO_3$/liter; 65-percent transmissivity (ocean water), 200 μg $CaCO_3$/liter; 35-percent transmissivity (estimated mean for ebb flow through English Harbor Pass), 400 μg $CaCO_3$/liter. If these data can be applied to Fanning Island Lagoon, they would indicate that the visually striking increase in turbidity during ebb flow actually represents a relatively small admixture of water from the far interior of the lagoon.

ACKNOWLEDGMENTS

We especially thank Mr. Peter W. deWitt for his able help with the field measurements. We also are grateful for being able to count at all times on the cheerful and ready assistance of the other expedition members.

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